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Dynamics and Structure of Planetery Rings

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A. Saturn's Central Flash

We have recently completed an analysis of Saturn's central flash from the 3 July 1989 occultation by Saturn of 28 Sgr occultation. We succeeded in finding direct evidence in the infrared images themselves of multiple stellar images formed during the central flash as observed by us and our collaborators from McDonald and Palomar Observatories. The detailed characteristics of the central flash light curve depend on the shape of the planetary limb, as well as the precise occultation track followed by a given observatory. We found that variations in zonal wind speeds can significantly affect the times at which the starlight flickers between the gaps in the rings, and that the zonal winds above the cloud deck decay with height to a mean velocity of about 40 m s^{-1} at the northern latitudes sampled by the flash. Our results were published in *Icarus* (1995) **113,** 57-83.

B. Uranus' λ ring

During the 11 July 1992 occultation of U103 by Uranus, which we observed from CTIO, we observed a sharp drop in signal at the expected location of the λ ring on ingress, but not on egress. The equivalent width of the feature is a few tenths of a km, well above the noise level of our data. At nearby ESO, our collaborator F. Roques also observed a ring occultation at this location, but with a smaller telescope and under poorer observing conditions. From Palomar, P. Nicholson found no trace of a ring occultation at this location. We have concluded that the λ ring is clumpy – it has azimuthally varying optical depth. This work has been accepted for publication in *Icarus* (1996): ''Earth-based detection of Uranus' Lambda Ring'' by R. G. French and seven co-authors.

C. SAAO observations of the 9 September 1995 Uranus occultation

As part of our continuing campaign of observing stellar occultations by Uranus and Neptune, we were awarded observing time at the South African Astronomical Observatory (SAAO) for the 9 September 1995 Uranus occultation of U134. This is a bright star (m_K=8.1) and we successfully obtained quite good SNR for both the rings and the atmosphere. We are incorporating these results into our global ring orbit model for the Uranus system, to be developed during the coming year.

D. Saturn's upper atmosphere

We have continued our collaboration with W. Hubbard in the joint analysis of all available 28 Sgr Saturn atmospheric light curves. These results have been used to characterize the mean temperature, wave properties, turbulence, and energetics of Saturn's upper atmosphere. As part of the final reduction of the McDonald Observatory data and performed a complete analysis of the Lick Observatory 28 Sgr occultation observations, provided by R. Stover and J. Cuzzi, which were obtained at 0.89 μm with a CCD camera at a time resolution of 1.0 sec. These data are of excellent photometric quality. The results are in final preparation for publication.

E. Structure and opacity of Saturn's rings

Saturn's ring particle properties have been carefully studied using both UV and RSS Voyager occultations, as well as from Voyager images in both reflected and transmitted light, but because of limited SNR for the Voyager occultations, most of the results in hand are confined to relatively translucent regions of the rings. We have begun to use IR and visual 28 Sgr observations to extend the wavelength coverage of the measurements of ring opacity, including even the nearly opaque regions of the B Ring, where we are still able to detect a stellar signal. By carefully determining the radial variations in optical depth from our three occultation data sets, all taken under similar viewing geometry, we have measured the wavelength-dependence in opacity throughout the ring system. Much of the stellar signal from the optically thick regions of the rings is the scattered component, rather than the strongly attenuated direct signal. By matching our calculated scattered signal to the inferred scattered signal, we are able to estimate the mean optical depth and scattering efficiency, Q, for selected regions throughout the entire ring system.

F. Edge waves and librations of the Uranian rings

The ε ring is the widest and most eccentric of the Uranian rings, with two attendant shepherd satellites which serve to keep the ring sharp-edged and confined. Using nearly 50 high SNR occultation profiles of the ε ring obtained between 1977–1993, we have searched for waves in the outer and inner edges of the ring with the expected pattern speeds, amplitudes, and phases predicted by shepherding theory. Important consistency checks are that the longitude of the maximum or minimum of the disturbance be aligned with the corresponding shepherd satellite in its orbit, that the pattern speed be within the uncertainties in the satellite's mean motion, and that the amplitude of the edge wave be comparable to theoretical predictions. All of these tests are passed for both edge waves. For example, in the fit for the 14:13 inner eccentric resonance (IER) of Ophelia with the outer edge of the ring, the observed edge wave amplitude is 0.5 ± 0.2 km, compared to the predicted value of $A_L^{1/2} = 0.58$ km, the longitude of the wave is $297.58 \pm 1.20°$ compared to the satellite longitude at epoch of $298.369 \pm 0.072°$, and the fitted pattern speed of the wave is $956.41707 \pm 0.00095\ °\ d^{-1}$ compared to the satellite mean motion of $956.4068 \pm 0.0374\ °\ d^{-1}$. We feel that there is good reason to believe that edge waves are present in the ε ring, but post-fit residuals remain larger than measurement uncertainties, and other physical effects may be at work.

G. Saturn ring plane crossing observations from Palomar

In collaboration with Phil Nicholson, we obtained telescope time at Palomar to observe the Saturn ring plane crossings in 1995. We made near-infrared and visual CCD imaging observations of the rings and small inner satellites during the Earth crossing in August 1995 and also near the sun crossing of November-December 1995. The trajectory of Prometheus is of special interest because that moon has the largest predicted secular acceleration, but better knowledge of the other small inner moons would provide better estimates of the masses of the co-orbital moons from their mutual perturbations, investigation of the near 3:2 resonance between Pandora and Mimas, and a better understanding of the motions of Prometheus and Pandora relative to the F Ring, which they shepherd.

We also obtained radial profiles of the near edge-on brightness, or 'photometric thickness' of the main rings, from which we hope to extract information on the expected vertical warping, on bending wave amplitudes, and on the vertical extent of the spokes in the B Ring. From precise determination of the time of ring plane crossing, we should be able to improve our recent determination of the precession rate of Saturn's pole. We will also obtain long-exposure image mosaics of the faint E Ring in order to determine its JHK colors, relevant to particle size models, and to determine the ring's radial and vertical structure.

H. HST observations of Uranian rings

On 14 August 1994, thirty-three images were taken of the Uranus system in four colors with the WFPC2 on the Hubble Space Telescope (Pascu *et al.* 1995). Eight of the ten faint, inner satellites of Uranus have been detected in the images, and astrometric and photometric analysis has been carried out to improve their orbits for later detailed spectroscopic study and to study their dynamical resonances. In a collaborative arrangement with Dr. Ken Seidelmann as the PI of the team that took the HST images, I have agreed to carry out the following tasks:

Uranus ring photometry

- Determine the plate scale and orientation of each image and the pixel location of the center of the planet, based on satellite astrometry, and taking account of field distortion in the optics.
- Coalign the images, subtract scattered light, and remove diffraction pattern.
- From the latest ring orbit model, and observations of the variations of ring width with longitude, to compute the predicted location in each image of the ring periapse (particularly for ε, α, and β, the three widest rings).
- Compute the *predicted* ring brightness as a function of position angle, based on simple ring particle scattering laws.
- Convolve the predicted brightness with the point spread function of the instrument to construct a model image to be compared with the observations.

- Construct radial scans and azimuthal averages of the rings as a function of ring longitude to determine the integrated ring brightness as a function of position angle, and compare these results with the models. Subtraction of scattered light is likely to be the limiting problem.
- Do relative photometry, based on the satellites in the images, for the four colors.
- Estimate albedo of ring as a function of wavelength. This will require some radiative transfer calculations to do properly.

Search for Cordelia and Ophelia

- Sub-pixel registration of frames, construction of "template" image, and image subtraction.
- Scaling and template image subtraction ("blinking") to search for faint satellites.
- If Cordelia and Ophelia are not found in this fashion, there is still the chance of detecting them by co-adding the light from several images, using apertures that are positioned appropriately to follow the motion of the satellite between images. This could improve the SNR by a factor of up to $(33)^{1/2} = 5.7$ if all 33 images are combined, bringing the satellites into the realm of detectability even if in any single image they have an SNR of less than unity. Given the uncertainty of the longitude of the satellite in any one image, the entire set of possible satellite longitudes would have to be tried, but if a convincing peak were found in the light for a single longitude, the results could be convincing.
- Determine pixel locations of centroids of satellite images.
- Determine corrections to the mean motions of the satellites.

The main goal of the ring photometry is to compare the colors and reflectance properties of the rings and the small satellites. The coexistence of large satellites, small satellites, ring particles, and dust in the ring system makes it quite likely that there are common characteristics in their spectra, but this remains to be established. The search for Cordelia and Ophelia is especially important because if we can pin down the orbital period of either of these two satellites, it would provide a critical test of whether or not edge waves have really been detected in this ring.

PLANETARY GEOLOGY AND GEOPHYSICS PROGRAM

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Planetary Geology	Geologic Mapping	Planetary Geophysics	Remote Sensing	Solar System Dynamics	Planetary Cartography
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Full Proposal	Technical Report
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